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SOME FLUID MECHANICAL PROBLEMS RELATED TO SUBSONIC AND SUPERSONIC AIRCRAFT

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SOME FLUID MECHANICAL PROBLEMS RELATED TO SUBSONIC AND SUPERSONIC AIRCRAFT

Report to the
NASA Subcommittee on Fluid Mechanics of the Committee on Basic Research
by the
Ad Hoc Committee on Subsonic and Supersonic Aeronautics

Edited by
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PREFACE

This report is an outgrowth of two presentations before the NASA Subcommittee on Fluid Mechanics. The first was held at the Boeing Scientific Research Laboratory in May 1967 and the second at NASA Headquarters in Washington in November 1967. At the latter meeting an ad hoc group was authorized to distill the significant aspects of these presentations and to prepare a report thereon. Early in January 1968 the group was organized and a plan for performing the work developed. In particular, it was agreed that additional information as could be conveniently obtained by individual members of the group from aircraft manufacturers, from the United States Air Force, and from the Air Systems Command of the United States Navy was to be included. In addition, it was agreed to exclude from consideration certain problem areas, for example, those connected with noise, atmospheric effects, V-STOL aircraft, and rotating machinery; not that important and interesting fluid mechanical problems do not exist in these areas, but it was believed that only by selecting a reasonably defined scope would these considerations by useful.

Members of the Ad Hoc Committee on Subsonic and Supersonic Aeronautics were as follows:

Chairman: Paul A. Libby, University of California, San Diego
Robert Korkegi, Aerospace Research Laboratories
Kenneth Lobb, Naval Ordnance Laboratory
Harold Mirels, Aerospace Corporation
Simon Ostrach, Case Western Reserve University

SUMMARY

Some of the problems which are connected with modern subsonic and supersonic aircraft and which have their origin in fluid mechanical phenomena are reviewed in order to indicate topics and areas of research requiring attention. Certain problems have been excluded either because it is well-known that sufficient attention is being devoted to them or because they lie outside the domain of competence of the authors. In brief, the following topics are discussed and found to require further study:

1. Turbulent boundary layers, including the effects of three-dimensionality and adverse pressure gradients.
2. Separated flows, such as are due to adverse pressure gradients (e.g., on inlets and on airfoils at high angles of attack), to shock-boundary layer interactions including the transonic problem, and to concavities, and so forth, and including three-dimensional effects.
3. Vortex flows, such as arise from wings and fuselages at angles of attack.
4. Correlation of wind-tunnel measurements with flight data and other wind-tunnel data.
5. Transonic flows, including two-dimensional airfoil design, integration of wings and fuselage, and methods of increasing the critical Mach number.

INTRODUCTION

Much of the fluid mechanical research of the past 15 years motivated by aerospace problems has been related to hypersonic flight. In particular, the entry of bodies into the atmosphere from ballistic, satellite, and space trajectories has provided the applied basis for much research. Thus, aerodynamic heating, radiation gas dynamics, aerothermochemical effects, ablation phenomena, and so forth, have occupied the attention of many fluid mechanicians in the aerospace community. This attention to hypersonic phenomena left many unsolved and partially solved problems of subsonic and supersonic flight. The renaissance of high-performance military aircraft for use in limited warfare and the initiation of the first of several generations of supersonic transports have resulted in renewed interest in these problems. The purpose of this report is to present briefly some of the fluid mechanical problems associated with subsonic and supersonic aircraft.

In organizing a report of this sort there are a variety of topical arrangements possible; for example, topics could be considered according to the number of dimensions involved and to whether viscous effects are important. Five topics have been chosen which appear to provide a framework for discussing most of the fluid mechanical problems connected with aircraft; a section is devoted to each of these topics. However, the topics are closely interrelated and the framework convenient only for purposes of exposition, that is, the topical division is not to be taken too literally.

Many of the practical problems related to aircraft design and development are of great complexity and their solutions depend primarily on ad hoc methods, wind-tunnel testing, and flight test. Fluid mechanical research motivated by these problems can only be expected to provide insight and understanding of the phenomena involved and to suggest the most promising solutions of practical problems; it can be expected neither to provide immediate solutions of existing problems nor to lead to designs which will avoid future problems. Thus when the need for further research on a particular problem is discussed, it is not implied for all cases that experimental data of use to the designers do not exist but rather that the understanding and methods of analysis are inadequate for the rational use of these data beyond the range of parameters covered. In general, this review is presented to show that more attention should be devoted to fluid mechanics motivated by aircraft problems; the intent is to expose some of the areas requiring such attention.

The operating conditions of subsonic and supersonic aircraft are such that their associated viscous phenomena are predominantly turbulent; thus, turbulent flows will be emphasized. However, there are cases, for example, in wind-tunnel tests and in the study of separated flows, where the consideration of laminar flow phenomena can be justified for a variety of reasons.

This review is confined to subsonic and supersonic flows and excludes hypersonic flow. Accordingly, compressibility effects will be of importance but will be associated with classical, perfect gas behavior; that is, the convenient assumptions of constant coefficients of specific heat, negligible dissociation, and so forth will generally be satisfactory.

Finally, this survey does not present a fluid mechanics research program related to aeronautics—although it could be useful in planning such a program. Moreover, the knowledgeable reader will recognize at once that the problems described in this paper are old. The purpose of this report is to focus attention on these problems once again, not only because they are interesting fluid mechanics research problems but, more, because they are important problems whose solutions are crucial to progress in the aeronautics industry.

TURBULENT BOUNDARY LAYERS

The turbulent boundary layer has played a central role in fluid mechanical research for many years. This role is secured from an applied point of view by the importance of airfoil stall, subsonic and supersonic inlet and diffuser performance, skin friction, and related problems in aircraft and engine design. For low-speed incompressible flows, the basic problem has been the prediction of the point of separation when the external flow involves a distributed, adverse pressure gradient. A variety of successful methods exist for the prediction of boundary layer properties and behavior with either zero or favorable pressure gradients, but the adverse case provides a more rigorous test of validity and accuracy of a method of analysis. Various methods presently exist for these calculations. References 1 and 2 present recent reviews while reference 3 presents a recent, highly sophisticated method.[1]

The compressible case of applied interest for high-speed aircraft may in some cases be idealized to correspond to two-dimensional or axisymmetric flow; for example, on the spike or ramp of a supersonic inlet, three-dimensionality may be inessential. Reference 4 provides an indication of the status of this problem and a rather complete bibliography.

It is fair to state that even for these idealized, two-dimensional or axisymmetric cases much work remains to be done (cf. comment by Clauser in ref. 2) before predictions of boundary layer behavior can be made with confidence; for example, predictions of the gross properties of skin friction and heat transfer for a flow involving significant adverse pressure gradients. Knowledge of turbulent shear flows is such that it suggests that emphasis be placed on experimental research. In this regard, new techniques of data collecting and analysis based on modern signal processing are providing means for improved experimentation. Indeed, the limited knowledge of the detailed structure of low-speed turbulent flows depends on the early work of Favre, Gaviglio, and Dumas (ref. 5) who combined hot-wire anemometry and analog tape recording. More recently Coles and Van Atta (ref. 6), Frenkiel and Klebanoff (ref. 7), and Fisher and Davies (ref. 8) have employed more modern developments in recording and analysis.

The discussion thus far has emphasized turbulent boundary layer behavior in pressure gradients which are adverse but distributed over considerable streamwise distances. However, there are many supersonic flows for which shock waves from interfering surfaces impinge on turbulent boundary layers. In these cases the adverse pressure gradient is highly localized and the aforementioned methods of analysis are inapplicable. This problem of shock impingement on turbulent boundary layers, even for essentially two-dimensional flows, is largely unsolved and requires further research. At the present time only experimental data on the pressure rise for incipient separation without heat transfer appear available. Contributing to the complexity are the interaction between the external supersonic flow and the boundary layer upstream of the shock impingement point, and local separation and reattachment of the boundary

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[1]The references cited are a partial up-to-date bibliography which provide entry points into the more complete relevant literature.

layer if the incident shock is sufficiently strong. Another example of turbulent boundary layers subjected to localized adverse pressure gradients arises when control surfaces, lateral control jets, and discharge doors are deflected thus causing an upstream shock which interacts with the oncoming boundary layer. Under these circumstances adequate descriptions of the boundary layer profiles through the interaction region are unavailable.[1]

In connection with turbulent boundary layers subjected to severe adverse pressure gradients, the important problem of the prevention of separation by means of tangential blowing must also be mentioned. The addition of momentum to a boundary layer encountering an increasing pressure is an old suggestion based on early boundary layer developments, but its exploitation to overcome separation in connection with modern aircraft, for example, on inlets and relative to high lift devices, appears to require further study and research. Reference 9 provides innumerable references to the use of blowing.

Most of the applied problems relating to subsonic and supersonic turbulent boundary layer flows contain three-dimensional effects; that is, the mean flow involves three velocity components, and the pressure field generally involves gradients in two directions parallel to the surface. The boundary layer on a swept wing provides an important example of three-dimensional flows dominating many performance and control aspects of modern aircraft. The present status of three-dimensional boundary layer theory has been reviewed most recently by Cooke and Hall (ref. 10) and previously by Moore (ref. 11). If the coordinate system chosen for the description of a three-dimensional boundary layer is fixed to the streamlines and normals thereto of the flow just outside the boundary layer with a third coordinate normal to the surface, the describing equations can be greatly simplified by a small crossflow assumption and, in fact, most progress has been based thereon. This assumption changes considerably the nature of the analysis of the three-dimensional boundary layer; instead of a three-variable (x, y, z) problem, a series of two variable problems in streamlines of the external flow and normals thereto must be considered. The first step in a calculation thus involves detailed knowledge of the inviscid streamline patterns on the surface of the body; generally, these are not easy to obtain from either calculations or wind-tunnel tests. The description of the streamwise flow along each streamline corresponds to an axisymmetric calculation; thus, the difficulties associated with these for the case of adverse pressure gradients, as discussed previously, apply in three-dimensional flows. In addition, basic problems relative to the crossflow are as yet unsolved. In particular, suitable forms for the crossflow velocity profiles, that is, forms which

[1]Near the throat of a supersonic inlet, multiple shock—boundary-layer interactions can arise. There has been no treatment of this case even for laminar flow.

permit S-shaped velocity distributions to be treated by practically important integral methods, have not yet been established. A more fundamental question concerns the phenomenology of the eddy transport coefficients in three-dimensional flows and whether scalar representations of them are adequate.

Thus it can be stated that, even with the small crossflow approximation, our understanding and methods of analysis for the treatment of three-dimensional turbulent boundary layers are unsatisfactory. In the more general case, for example, near separation, wherein the two velocity components tangent to the body and along and normal to the direction of the external streamlines are of the same magnitude, the complete three-variable problem must be considered and even more information is necessary.

Turbulent boundary regions, in contrast to boundary layers, have important applied implications in the field of three-dimensional effects. The flow is the junction of a lifting surface, and a fuselage is an example of such a boundary region. It is characterized in a fundamental sense by two small dimensions, normal to each of the intersecting surfaces, in contrast to a boundary layer which has one small dimension, that is, normal to the surface. The present situation relative to these flows appears to be that, even for the laminar case with a uniform external stream, a complete analysis is not available (see Rubin, ref. 12), and that for more general cases of turbulent flow and pressure gradient much research remains to be done. Even the essentially inviscid but supersonic flow in corners involving intersecting shocks in different planes is an interesting, fundamental, three-dimensional flow with considerable applied significance. The recent work of Charwat and Redekeopp (ref. 13) gives an indication of the complexity of such flows. Finally, such corners can be the source of severe separation, of vortices causing interference on downstream control surfaces, and of buffeting[1].

In concluding this discussion of turbulent boundary layers, several additional areas requiring attention are noted. In view of the high Reynolds numbers attendant with flight application there is need for knowledge of boundary layer characteristics with Reynolds numbers based on typical streamwise lengths of up to 10^8. While there appear to be data available on the skin friction at high Reynolds numbers for Mach numbers up to 3 for constant pressure conditions, these should be extended to higher Mach numbers to include pressure gradients and to include in a systematic way the effects of roughness. Although throughout the supersonic regime accurate information on turbulent heat transfer is not generally essential from the point of view of structural integrity, it does become significant in certain localized regions of the aircraft, for example, in

[1] From an applied point of view one may be interested in how to change the configuration of the corner, e.g., by filleting, to avoid these difficulties.

fuel storage areas. Thus heat transfer data at high Reynolds numbers including the effects of roughness and pressure gradients are needed.

SEPARATED FLOWS

In the previous section concerning turbulent boundary layers an allusion has been made to flow separation associated with distributed and localized adverse pressure gradients. Because of the close interdependence of boundary layer behavior and separation, we are unable to compartmentalize our presentation more adequately. This section presents more fully the fluid mechanical problems of separated flows requiring attention.

The fundamental problem of separated flows is that the usual point of view of boundary layer theory does not apply. The original scheme of Prandtl is based on the a priori calculation of an inviscid flow in order to provide the pressure distribution for a subsequent boundary layer calculation. When the flow conditions are such as to cause extensive separation, this scheme fails; there is no apparent means of selecting a configuration for the calculation of the inviscid flow (see, e.g., ref. 14).

A second fundamental problem is that in many separated flows there is within the "boundary layer" a reverse flow, that is, regions which are influenced by the flow at stations downstream of the station in question. Such an influence violates the parabolic nature of the boundary layer and leads to essential difficulties.

These fundamental problems have been overcome in an appropriate manner for certain idealized, laminar flows involving supersonic external streams by the use of integral methods (see, e.g., ref. 15), but the success of these methods may be due to a lack of definition; that is, if more refined methods, for example, higher moments, are used, the predictions may not become more accurate but rather less accurate until finally the analysis fails completely. In connection with these fundamental questions, reference 16 is of considerable interest. The authors employed a finite difference procedure to compute for incompressible flow the laminar boundary layer properties and the pressure distribution with and displacement thickness specified and found no singularities at separation and no numerical difficulties. Whether the calculation can be repeated with the computed pressure distribution now specified is unknown.

When separation involves turbulent flow, these fundamental difficulties are compounded by the lack of adequate means to describe the turbulent transport properties as discussed in the previous section. It must be concluded then that even for rather idealized cases the knowledge and understanding of turbulent separated flows is inadequate. Clearly, in flow situations of applied interest, involving, in general, three-dimensionality, compressibility, and heat transfer, the situation is worse.[1]

[1]It is interesting to note that the definition of separation line in three-dimensional situations is not trivial. The reasonable definition appears to be that it is an envelope of surface streamlines.

Examples of such separated flows of applied interest are numerous; reference 17 provides a valuable review of some cases of three-dimensional separation. Some examples are shock-boundary-layer interaction, the flow ahead of deflected control surfaces leading to compression, forward and backward facing steps, the flow behind bluff bodies, the flow at the nose of a wing-fuselage junction, airfoils at high angles of attack and/or with large flap deflections, and cones at angles of attack of the order of the cone half-angle. In all these examples the Reynolds number of the flow plays an important role in determining the point of separation, the extent of the separated region, and the point of reattachment if any. If adequate theories were available to describe even idealized models of these flows, the effect of changes of Reynolds number could be estimated; but since this is not the case, experimental data is depended on heavily for the answers to applied questions. It appears, however, that for many aircraft problems the existing data are not adequate for a sufficiently high Reynolds number. Many of the difficulties associated with the correlation of wind-tunnel results and of those from flight tests are due to inadequate simulation of Reynolds numbers with resultant improper simulation of flow separation.

Three-dimensional effects in separated flows perhaps provide a means for alleviating in many cases the deleterious effects of separation. For example, the recent experiments of Johnson (ref. 18) on a flat plate with a trailing edge flap with and without side plates clearly indicate that the extent of the separated region is greatly reduced when the side plates are removed, allowing spillage across the sides of the plate. Another example is given by the analysis of reference 19, where outflow from a plane of symmetry with an adverse pressure in the streamwise direction is shown to eliminate the separation which would have occurred without the outflow. In fact, three-dimensional separation is much less catastrophic and abrupt than are two-dimensional and axisymmetric cases. However, before such effects can be exploited to favorable ends, considerably greater knowledge and understanding of three-dimensional turbulent flows and their associated external streams must be obtained.

In addition to being influenced by three-dimensional effects, stable flow configurations involving separation can be greatly influenced by small amounts of mass transfer into and out of the separated region. This idea has been used to reduce the base pressure behind bluff bodies[1] (ref. 20) and the extent of separation ahead of a deflected flap (ref. 21). Presumably such control of separation has not found application in actual aircraft design because of the reluctance on the part of designers to introduce the requisite control devices and system complexity and because of a lack of adequate information for design purposes. Nevertheless, the influence of mass transfer on separated flows should be considered further.[2]

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[1]This too is an old suggestion; some work was carried out at the Ballistic Research Laboratories in 1951.

[2]When the separation is three-dimensional and involves lateral spillage, mass transfer may have considerably reduced efficacy.

This section on separated flows is concluded by emphasizing the need for further research on a variety of flows involving separation, and separation and reattachment. Mach number, Reynolds number, and heat and mass transfer effects all require further study.

VORTEX FLOWS

In many configurations of applied interest, flow separation leads to a vortex system which greatly alters the pressure distribution over the body and thus dominates the flow field (see ref. 22)[1]. Examples of vortex flows are the leading edge vortex on a delta wing at an angle of attack, the vortices on the leeward side of a circular cone at angle of attack, and the vortices at the junction of a wing and fuselage. In addition to altering the flow on the element generating them, vortices can interact with downstream surfaces and thus influence the flow over entire configurations with important consequences. For example, complex stability and control problems of aircraft arise because the vortices from the wing and/or the wing-fuselage junction alter the flow over the horizontal and vertical control surfaces. Reference 23 includes additional examples. The vortex system from a canard can change the flow over a main lifting surface. The vortices from the nose of a fuselage can interfere with the vortex system associated with the wing leading edge and alter the characteristics of the wing from those which prevail for the wing alone (cf. ref. 24). Finally, the vortices from the nose of a fuselage can be ingested into the engine inlet on the fuselage and degrade engine performance.

Vortices arise because of viscous effects, but in many cases their influence can be estimated in terms of inviscid flow theory provided that the separation point is known a priori and provided a model for the vortex system can be established a priori. The flow about a thin delta wing with sharp leading edges at an angle of attack provides an example on which both of these provisos are realized. The separation point, and hence the origin of the vortex sheet, is at the leading edge itself; the vortex sheet can be idealized to be nearly conical and to terminate in a vortex core located above and inside the leading edge. Slender body theory is employed for this example. Finally, these vortex sheets are fed by and connected with the wing leading edge and are subject to conditions of continuity and force equilibrium which are sufficient to determine the flow field and which lead to satisfactory agreement between theory and experiment (cf., e.g., ref. 25).

Recently, Polhamus (ref. 26) provided an ad hoc but useful analogy between vortex lift and leading edge suction which is not based on slender

[1]Reference 22 provides a series of papers which concern vortex motions and which were given at an IUTAM Symposium on "Concentrated Vortex Motions in Fluids," held at The University of Michigan in 1964. An extensive bibliography derives from these papers.

body theory and which provides excellent agreement with experimental results of wing lift on delta wings for platforms of practical interest.

When the location of separation is not known a priori, the analysis becomes nearly intractable. One can conceive of an iterative scheme involving alternate treatment of inviscid flow and boundary layer but, even for highly idealized configurations such as clean cones or cones with strakes, this scheme is not practical. The present situation relative to clean cones is presented in reference 27, where it is shown that, provided the separation point is known, a two-vortex system leads to a description of the flow field in some cases but does not provide the basis for iteration since the vortex model is too simplified.

In applied problems cases arise wherein two or more vortex systems interact, for example, when the vortex system from a fuselage interferes with that from the leading edge of the wing, and when secondary separation on the upper surface of a delta wing causes a second vortex system. In these cases, the location and strength of the vortices are dependent on the Reynolds number, at least until turbulent behavior dominates. Furthermore, it is important to emphasize that when flow separation is fixed not by body geometry but rather by boundary-layer behavior (e.g., as on bodies of revolution at angles of attack), the vortex formation, and consequently the entire flow, is sensitive to the nature of the boundary layer and thus to Reynolds number.

The problem of vortex breakdown should also be mentioned. At high angles of attack the portion of the vortex system influenced by the trailing edge increases until the pressure rise near the trailing edge destroys the conicity of the flow and leads to wing stall. This phenomenon has been described by Hall in references 22 and 28 but does not appear to be well understood and, moreover, has not been related to the applied problem of wing stall.

A remarkable aspect of vortex behavior is that, under conditions which would be expected to lead to entirely symmetric behavior, a vortex pair in fact is not symmetrically disposed and consequently the entire flow is asymmetric. This occurs behind slender bodies at large angle of attack under some conditions (cf., e.g., ref. 27). Clearly the asymmetric vortices are associated with asymmetric separation points, asymmetric pressure distributions, and lateral forces and yawing moments.

Finally, the decay and rolling up of a trailing vortex system is sometimes important in assessing the influence of the vortices on downstream surfaces. There do not appear to be adequate methods for treating these matters.

Thus, a need exists for continuing research on vortex flows, their connection with separation and their behavior in the presence of other vortices and of surfaces such as wings and fuselages.

COMPARISONS OF WIND-TUNNEL AND FLIGHT DATA

Use of the wind tunnel to provide a valid basis for precise prediction of flight characteristics of practical aircraft and the techniques of conducting wind-tunnel investigations for that purpose are currently being critically scrutinized as a result of reported disparities between wind-tunnel and flight test results throughout the currently attainable flight regimes.

In the wind-tunnel testing of generalized research aircraft configurations and in establishing a configuration for a practical aircraft, trends in the resulting data have generally been considered of principal importance. However, in cases involving practical aircraft, for which the configuration has been fixed, absolute levels or incremental changes naturally are the principal focuses of attention. Growing emphasis on highly definitive values of aerodynamic coefficients has accompanied the development of the recent generation of high-performance aircraft. As a result of this emphasis, data tolerances have become more and more restrictive, and apparent data discrepancies have been assigned greater importance than in the past. The situation is aggravated by the growing demand for wind-tunnel test time causing aircraft developers to conduct investigations of particular models in several different wind tunnels. Quite naturally, data for the "same" configurations tested in the different facilities are compared and any significant disagreement provokes justifiable dismay.

Disparities between wind tunnel and flight and between different wind tunnels may be due in part to testing techniques, wind-tunnel wall effects, aeroelastic phenomena, scale effects, wind-tunnel turbulence, inability to simulate on a model all features of the full-scale vehicle, and so forth. Continuous attention must be devoted by wind-tunnel specialists to removing these sources of disagreement[1]. For example, in practically all wind-tunnel tests the Reynolds number of flight is not simulated. Even so, under some idealized conditions, the force measurements on the wind-tunnel model can be corrected in a satisfactory manner for the differences in skin friction between model and full scale. These idealized conditions, require the absence of separation so that the basic notions of boundary layer theory apply, accurate knowledge of the transition location on both the wind-tunnel model and full-scale body, and a configuration permitting accurate skin-friction calculations, for example, a slender, straight fuselage with a high aspect ratio wing. If the Reynolds number for the model is within an order of magnitude of that of interest for the full-scale aircraft, and if cruise conditions which generally involve low angles of attack and small deflections of control surfaces are being

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[1]Disagreement between wind-tunnel results sometimes arises because secondary results from one test series, e.g., drag data from a test for directional stability, are compared with primary and presumably accurate results from a second test series. The comparison is frequently poor.

studied, then the size of the corrections to the force measurements can be reduced and test interpretation made more accurate by using boundary layer trips to fix transition on the model at its estimated location in flight. On the other hand, if the Reynolds number simulation is inaccurate by several orders of magnitude or if separation plays an essential role in the determination of the flow field about either the model or the full-scale aircraft, then the use of boundary layer trips may not improve the simulation. Moreover, in the latter cases no simple scale corrections are possible and significant disparities between wind-tunnel and flight results can occur.

Differences in test techniques (e.g., the model support system, the tunnel blockage, etc.) can cause discrepancies between tests in two different wind tunnels at the same Reynolds number and can invalidate the comparison; efforts must be continuously directed toward removing this source of error. Nevertheless, there can be discrepancies due to differences in the location of transition during the two tests which are fluid mechanical in origin; this report is concerned with these. In addition, studies of the separation behavior and vortex formation in laminar flows, while not directly relevant to flight conditions, can be justified by their relevance to wind-tunnel testing.

It will be valuable to review first several examples reflecting the present situation in wind-tunnel testing. From experience with the XB-70, there is evidence that prediction of drag at supersonic speeds, based on wind-tunnel results, can be made reliably. In the case of the XB-70, the M = 3 drag data obtained in wind tunnels is within 2 percent ($\Delta C_D \simeq 0.0003$) of the mean of the flight data. This result is based upon preliminary analysis of a portion of the available flight data.

At transonic speeds, considerable emphasis has been placed on drag measurement, particularly the drag-rise characteristics of transport aircraft designed for flight at high subsonic speeds. Mixed results have been reported from comparisons of wind-tunnel and flight data. According to one aircraft manufacturer, drag-rise characteristics determined in wind-tunnel tests have been in good agreement with flight results for some configurations and in relatively poor agreement for similar configurations.

The emphasis on drag prediction for present-day high-performance aircraft has led to the common, but perhaps unreasonable, request by aircraft developers for wind-tunnel drag coefficient measurements accurate to ±0.0001. Accuracy notwithstanding, repeatability of the wind-tunnel data is generally at best only about ±0.0002 for drag coefficient. Efforts are being made to improve the precision of drag measurement in the wind tunnel, but even then, according to reference 29, agreement of wind-tunnel-based predictions with flight results will likely be no better than about ±5 percent as a result of imprecision of inflight measurements. Others believe that for the cruise conditions alluded to previously, a ±3 percent uncertainty in drag is achievable between true flight performance and the predictions obtained by the most knowledgeable wind-tunnel practitioners.

Of further concern at transonic speeds is the disparity in wing shock location noted between wind-tunnel and flight measurements. This phenomenon is considered to result from the difference in shock-wave boundary-layer interaction on the wing caused by the inability to scale properly the boundary layer thickness on the wind-tunnel model and to account for differences in the location of boundary layer transition. Interest centers primarily on the pitching moment and lift rather than on drag. Recent work at the Langley Research Center indicates excellent success in the simulation of these flows at subscale Reynolds numbers if the transition strips are located far enough downstream to maintain the same ratio of turbulent boundary layer thickness to wing chord as is estimated to prevail under flight conditions. Further discussion of this problem is included in reference 30.

At subsonic speeds, dependence on Reynolds number is sometimes found in lift and pitching moment data. However, anomalous behavior occurs; in at least one case, excellent agreement between the high Reynolds number wind-tunnel data and the flight results was achieved when the wind-tunnel model was tested without a specific boundary layer trip. Inclusion of a leading edge boundary layer trip reportedly resulted in less satisfactory agreement. The corresponding pitching-moment data from flight have been described by the aircraft manufacturer as characteristically the same as the higher Reynolds number wind-tunnel data. Other unpublished proprietary data, indicative of low-speed configurations, range from firm indications of pitch-up in wind-tunnel data to strong pitch-down characteristics in flight. These deviations are consistent with generally acknowledged concerns for a high degree of uncertainty in data obtained under test conditions involving separated flow as a result of the inability to simulate properly the boundary layer. There continues to be a question as to precisely how to apply corrections to pitching-moment data in conventional closed wind tunnels, particularly for models with highly swept wing elements.

The data of reference 31 are indicative of generally good agreement in drag measurements for models tested in various NASA facilities throughout the current operational flight-speed regimes, particularly for relatively slender configurations. Other data from tests in the Langley 8-foot and 16-foot transonic facilities, reported in reference 32, reveal significant quantitative disparities at the highly important cruise conditions for a high subsonic-speed transport aircraft. Although those data are reported as in good agreement, there is reason to ask if "good" is good enough. Considering the values of model blockage for the two facilities, 1.7 percent and 0.4 percent, there arises the question of the influence of, and correction for, model blockage.

Additional data from recent carefully controlled investigations of a Lockhead C-5A model in the Ames 11- by 11-foot, the AEDC 16-foot, and the Cornell 8-foot wind tunnels are presently being summarized and analyzed at the Ames Research Center. In the investigations, the identical model and sting support were used in the three wind tunnels. Boundary layer transition was fixed on the model elements on the basis of a thorough grit drag elevation in the Ames facility involving flow visualization of the boundary layer condition through the use of subliming solids. The grit drag evaluation was verified in the Cornell facility. Although the analysis is incomplete, major discrepancies in pitching-moment data are found among the facilities. Furthermore, pressure surveys in the vicinity of the model obtained in both the Ames and Cornell facilities are suggestive of a difference in blockage influence.

The use of wind tunnels to provide force and moment data on complete configurations has been emphasized here. But there are other important results which are obtained in tunnel testing and which are subject to the same disparities as such measurements. Examples are static longitudinal and lateral stability characteristics, basic control and trim properties, stability derivatives, maximum lift in the presence of the ground, and aeroelastic effects on stability and control and including flutter. All these involve problems in test technique and data interpretation; at a more fundamental level there prevail the same problems of separation, vortex behavior, and Reynolds number effects thereon as for force and moment data.

Thus, it is concluded that agreement between wind-tunnel and flight data and wind-tunnel and wind-tunnel data, although occasionally good, is inconsistent enough to provoke questions of confidence. Although improved test techniques and instrumentation are continually being explored and employed, there is obvious room for further improvement. In particular, the problem of the correct modeling of boundary layer flows in wind-tunnel tests, discussed in brief previously, continues to require consideration for many flight conditions and for many aircraft configurations. Present indications are that fixing boundary layer transition in order to simulate high flight Reynolds numbers is not generally adequate. Questions of if, where, and how to fix transition all need to be investigated relative to specific test objectives. It must be emphasized that the problem of boundary layer transition, although subject to much research over a period of 50 years, remains poorly understood. Whether knowledge of transition will ever be adequate and what additional research must be carried out to improve understanding are unanswerable. However, it is questionable whether additional transition data from routine wind-tunnel testing will prove useful since the environment in wind tunnels reflected in unit Reynolds number effects on transition does not simulate free flight conditions. A suggestion has been made that only if the boundary layer on the tunnel walls is laminar is transition data in wind tunnels reliable, but this suggestion has not received universal acceptance. It is probable that there are several mechanisms operative in altering transition behavior that are covered by the unit Reynolds number. This is strongly suggested by the remarkable and inexplicable correlation of transition data from wind-tunnel and ballistic ranges given by Potter in reference 33.

Transonic wall corrections have commonly been ignored in slotted and porous-walled wind tunnels along with blockage corrections. On the basis of recent data, there is reason to think that subtle errors might be included in data thought to be free from such corrections.

It is thus clear that fluid mechanical research on transition and on the previous topics of separation and vortex motion, particularly with reference to wind-tunnel testing, is fully justified by the important applied problems discussed herein.

TRANSONIC FLOWS

Phenomena associated with transonic flow are involved in the renaissance of interest in aircraft problems. Principal motivation for the study of transonic flows relates to the design of aircraft with the highest possible flight Mach number before a prohibitively high drag rise occurs. A useful collection of recent papers on transonic flows is presented in reference 34.

Consider first the case of two-dimensional flow. The optimum design of a transonic wing profile involves the determination of an airfoil shape with the highest Mach number associated with drag divergence for a given thickness ratio and lift coefficient. The fundamental problem under flight conditions relates to the interaction of a turbulent boundary layer, the almost normal shock being associated with transonic speeds. As the free stream Mach number increases, the strength of this normal shock and the extent of separation increase. When interaction leads to extensive separation and a large wake, excessive drag occurs and steady flight at higher Mach numbers becomes impractical. Associated with extensive separation is wing and control surface buffeting; it is thus desirable to have airfoils with distinct drag rise and buffet limits, the latter being at a higher Mach number than the former.

This fundamental problem of boundary layer-normal shock interaction makes the analysis of transonic flows and optimum airfoil design difficult. There presently exists for the treatment of some aspects of this problem a simplified procedure which is semiempirical, but useful for predesign calculations. This is the Sinnott-Osborne method given in reference 35 (see also refs. 36 and 37), but it should be extended on the basis of additional data covering a wider range of Reynolds numbers and wider class of profile shapes.

More accurate methods for two-dimensional airfoil design are desired. The basis for treating the inviscid flow probably resides in the use of the time-dependent methods for treating mixed elliptic-hyperbolic equations usually identified with Lax and Wendroff (ref. 38). Such methods would also permit analysis of ventilated wall configurations for transonic wind tunnels. However, for the detailed treatment of the real airfoil problem, these inviscid analyses must be combined with an analysis of a turbulent boundary layer subject to an abrupt pressure rise.

The difficulties associated with this problem were discussed earlier. In principal, some iterative scheme can be conceived, but whether it leads to reasonable results cannot be predicted at this time.

Three-dimensional effects play an important role in the use of transonic airfoil data in aircraft design. The fuselage (even if appropriately contoured according to an area rule) and the wing tips alter the normal shock position, the separation, and the pressure distribution from their two-dimensional values. It appears that these three-dimensional effects frequently lead to an underprediction of the wing drag based on two-dimensional airfoil data. There do not appear to be any methods of analysis applicable to these three-dimensional flows: the designer must depend on wind-tunnel results. It is assumed, of course, that for studies of two-dimensional configurations the airfoil shapes with superior performance will lead to superior wing designs, but whether this is certain is not clear.

Leading edge separation must also be considered for transonic speeds since transonic aircraft must frequently operate at high angles of attack, for example, in maneuvers and in gust loadings. Such flows involve both the leading edge and transonic problems; the complexity is compounded.

Transonic flow is also concerned with the problem of mixed flows such as those which arise in the treatment of conical bodies, for example, a circular cone at large angles of attack, a cone of elliptic cross section, and a delta wing with round leading edges. In these cases the velocity components in the unit sphere centered at the apex combine to yield both subsonic and supersonic Mach numbers; as a result the describing equations are of the mixed type which lead to difficulties in numerical analysis. There appear to be no adequate methods of analysis of these flows at the present time. Küchemann has discussed some of these problems in a contribution in reference 34. Some of these flows involve significant boundary layer interaction due to separation and resultant distortion of the external flow; it will thus be difficult to compare the results of inviscid calculations with experimental results.

Many problems remain in the field of transonic flow that require attention and further research. Some, for example, the three-dimensional wing problem, probably call for experimental studies over wide Reynolds number ranges, whereas the airfoil and conical flows of the mixed type are amenable to theoretical research.

CONCLUDING REMARKS

In conclusion, several topics are cited which have not been mentioned in this review: those uncovered in the course of the presentations to the subcommittee and those uncovered in the preparatory or subsequent investigations. The first concerns unsteady phenomena. In general, the characteristic frequencies associated with aircraft maneuvers are such that quasistationary aerodynamic forces and moments can be considered to prevail. This is not to state that the static and dynamic stability derivatives for aircraft configurations are readily determined. In fact, we have some indication that this is not the case. Nevertheless, for their determination, quasistationary aerodynamics is generally adequate but improvements in wind-tunnel testing techniques and analysis are required. However, there are unsteady effects of practical importance, for example, those connected with oscillatory-shock boundary-layer interaction introducing deleterious effects on engine installations including so-called dynamic distortion. Flutter of control surfaces and trim surfaces continues to require attention and is probably also associated with unsteady separation and reattachment. Finally, there is the transient phenomena connected with abrupt control deflection or with entrance to a gust. These are fluid mechanical problems.

It is evident that additional research on methods of analysis of three-dimensional, inviscid, supersonic flow fields is required. It is probably fair to state that for two-dimensional and axisymmetric supersonic flows the methods of analysis based either on the method of characteristics or on finite differences are adequate and that, in principle, their extension to three-dimensional flows is straightforward. However, in practice, it appears that no satisfactory analysis exists for these more general cases which include embedded three-dimensional shock waves.

It appears clear from this discussion that there exists a need for wind-tunnel facilities with higher Reynolds number capabilities than are currently available. The studies of turbulent boundary layers, separation behavior, vortex flows, and transonic flows all require flows of high Reynolds number, preferably achieved at least in part by large-scale models. Furthermore, lack of Reynolds number simulation is probably the biggest single cause of disparities between wind-tunnel and flight tests, assuming that all possible care is taken in performing the former.[1] Therefore, a careful review is needed of existing and required subsonic and supersonic wind tunnels with capabilities for simulating the Reynolds numbers required for expected aircraft designs in the next 20 years. In this review attention should be given to the need for simulating dynamic quantities, in addition to Reynolds and Mach numbers; for example, there is presently an operational problem with military aircraft connected with the separation of stores at high speed. To study this problem in a wind tunnel, true velocity as well as Reynolds and Mach numbers appear necessary.[2]

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[1]It is emphasized that Reynolds number simulation does not solve all the problems of disparity discussed herein but that some problems cannot be studied with all available ingenuity without such simulation.

[2]It is perhaps appropriate to note that at its meeting on May 11-12, 1967, the NASA Research Advisory Committee on Fluid Mechanics adopted the following resolution:

The view which emerges from this brief survey is that challenging fluid mechanical problems related to the aerospace field, in general, and to subsonic and supersonic aircraft, in particular, abound and can well occupy the attention of the engineering and scientific communities for an indefinite period of time.

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"The Committee expresses its opinion that there is a serious need for a full-scale Reynolds number facility and suggests that it intensify its study of what is the most suitable type to build. It is strongly recommended that this facility be located at a NASA Research Center at which its capabilities can be utilized to the maximum benefit of government and industry."

REFERENCES

1. Rotta, J. C.: Turbulent Boundary Layers in Incompressible Flow. Progress in Aeronautical Sciences, Vol. 2 (A. Ferri et al., eds.), MacMillan Company, 1962.
2. Rotta, J. C.: Critical Review of Existing Methods for Calculating the Development of Turbulent Boundary Layers. Fluid Mechanics of Internal Flow (G. Sovran, ed.), Elsevier Publ. Co., Amsterdam, 1967, p.108.
3. Bradshaw, P.; Ferriss, D. H.; and Atwell, N. P.: Calculation of Boundary Layer Development using the Turbulent Energy Equation. J. Fluid Mech., vol. 28, no. 593, 1967.
4. Sasman, P. K.; and Cresci, R. J.: Compressible Turbulent Boundary Layer with Pressure Gradient and Heat Transfer. AIAA J., vol. 4, no. 19, 1966.
5. Favre, A. J.; Gaviglio, J. J.; and Dumas, R. J.: Further Space-Time Correlations of Velocity in a Turbulent Boundary Layer. J. Fluid Mech., vol. 3, no. 344, 1958.
6. Coles, D.; and Van Atta, C. W.: Progress Report on a Digital Experiment in Spiral Turbulence. AIAA J., vol. 4, no. 1969, 1966.
7. Frenkiel, F. N.; and Klebanoff, P. S.: Correlation Measurement in a Turbulent Flow using High-Speed Computing Methods. Phys. Fluids., vol. 10, no. 1737, 1967.
8. Fisher, M. J.; and Davies, P. O. A. L.: Correlation Measurements in a Non-Frozen Pattern of Turbulence. J. Fluid Mech., vol. 18, no. 97, 1964.
9. Lachmann, G. V.: Boundary Layer and Flow Control, Its Principles and Applications, Pergamon Press, 1961.
10. Cooke, J. C.; and Hall, M. G.: Boundary Layers in Three Dimensions, Progress in Aeronautical Sciences (A. Ferri et al., eds.), MacMillan Company, 1962.
11. Moore, F. K.: Three-Dimensional Boundary Layer Theory, Advances in Applied Mechanics, Vol. 4 (H. L. Dryden and Th. von Kármán, eds.), Academic Press, 1956.
12. Rubin, S. G.: Incompressible Flow along a Corner. J. Fluid Mech., vol. 26, no. 97. 1966.
13. Charwat, A.; and Redekeopp, L. G.: Supersonic Interference Flow Along the Corner of Intersection Wedges. AIAA J., vol. 5, no. 48, 1967.
14. Van Dyke, M.: Perturbation Methods in Fluid Mechanics. Academic Press, 1964, pp. 121-122.

15. Lees, L.; and Reeves, B. L.: Supersonic Separated and Reattaching Laminar Flows. I. General Theory and Application to Adiabatic Boundary Layer Shock Wave Interactions. AIAA J., vol. 2, no. 1907, 1964.
16. Catherall, D.; and Mangler, K. W.: The Integration of the Two-Dimensional Laminar Boundary Layer Equation Past the Point of Vanishing Skin-Friction. J. Fluid Mech., vol. 26, no. 163, 1966.
17. Rainbird, W. J.; Crabbe, R. S.; Peake, D. J.; and Meyer, R. F.: Some Examples of Separation in Three-Dimensional Flows. Can. Aeron. Space Journal., vol. 12, no. 409, 1966.
18. Johnson, C. B.: Pressure and Flow Field Study at Mach Number 8 of Flow Separation in a Flat Plate With Deflected Trailing Edge Flap. NASA TN D-4308, 1968.
19. Libby, P. A.; Fox, H.; Sanator, R. J.; and DeCarlo, J.: Laminar Boundary Layer Near the Plane of Symmetry of a Hypersonic Inlet. AIAA J., vol. 1, no. 2732, 1963.
20. Chapkis, R. L.; Fox, J.; Hromas, L.; and Lees, L.: An Experimental Investigation of Base Mass Injection on the Laminar Wake Behind a 6-Degree Half-Angle Wedge at M = 4.0. Presented at the AGARD Meeting, Ft. Collins, Colo., May 1967.
21. Ball, K. O. W.; and Korkegi, R. H.: An Investigation of the Effect of Suction on Hypersonic Laminar Boundary-Layer Separation. AIAA J., vol. 6, nos. 239-243, 1968.
22. Anon.: Progress in Aeronautical Sciences, Vol. 7, (D. Küchemann et al, eds.), Pergamon Press, 1966.
23. Nielsen, J. N.: Missile Aerodynamics, McGraw-Hill Book Co., Inc., 1960.
24. Hazen, D. C.: The Rebirth of Subsonic Aerodynamics. Astronautics and Aeronautics Journal., vol. 11, no. 24, 1967.
25. Smith, J. H. B.: Improved Calculations of Leading Edge Separation From Slender Delta Wings. R. A. E. TRN 66070, 1966.
26. Polhamus, E. C.: A Concept of the Vortex Lift of Sharp-Edge Delta Wings Based on a Leading-Edge-Suction Analogy. NASA TN D-3767, 1966.
27. Schindel, L. H.; and Chamberlin, T. E.: Vortex Separation on Slender Bodies of Elliptic Cross Section. MIT Aerophysics Laboratory TR 128, 1967.
28. Hall, M. G.: A New Approach to Vortex Breakdown. Proc. of the 1967 Heat Transfer and Fluid Mechanics Institute, Stanford Univ. Press, 1967.
29. Brown, C. E.; and Chen, C. F.: An Analysis of Performance Estimation Methods for Aircraft. NASA CR-921, 1967.
30. Loving, D. L.: Wind-Tunnel-Flight Correlation of Shock Induced Separated Flow. Conference on Aircraft Aerodynamics, NASA SP-124, 1966.

31. Bielat, R. P.; Luoma, A. A.; and Daugherty, J.C.: Drag Measurements from Different Wind Tunnels. NASA TM X-1271, 1966.
32. Luoma, A. A.; Re, R. J.; and Loving, D. L.: Subsonic Longitudinal Aerodynamic Measurements on a Transport Model in Two Slotted Tunnels Differing in Size. NASA TM X-1660, 1968.
33. Potter, J. L.: Observations on the Influence of Ambient Pressure on Boundary Layer Transition. AEDC TR 68-36, 1968. (Available from DDC as AD 666911.)
34. Küchemann, D.: On Some Three-Dimensional Flow Phenomena of the Transonic Type. Symposium Transsonicum. (K. Oswatitsch, ed.) Springer-Verlag (Berlin), 1964, pp. 218-248.
35. Sinnott, C.; and Osborne, J.: Review and Extension of Transonic Aerofoil Theory, ARC RM 3156, 1958.
36. Pearcey, H.: Shock-Induced Separation and Its Prevention. Boundary Layer and Flow Control, Vol. II (G. V. Lachmann, ed.), Pergamon Press, 1961.
37. Pearcey, H.: Aerodynamic Design of Section Shapes for Swept Wings. Advances in Aeronautical Sciences, Vol. III, Pergamon Press, 1962.
38. Lax, P. D.; and Wendroff, B.: Difference Schemes for Hyperbolic Equations with High Orders of Accuracy. Commun. Pure Appl. Math., vol. 17, no. 381, 1964.

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